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Micromechatronics in surgery

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There is a fast growing acceptance of minimally invasive surgery (MIS), in which surgical procedures are performed with the least possible damage to healthy organs and tissues. The reduction of recovery time, postoperative pain, infection risks and costs are some of the many advantages of MIS. Micromechatronic technologies involve the miniaturization of mechatronics devices like precision mechanisms, sensors, actuators and embedded electronics. They have played and will play a very important role in the advancement of MIS. They allow the possibilities of enhancing the surgeon's abilities where current MIS techniques do not permit the full range of human dexterity and perception. This paper discusses the objectives, roles, and some present and future applications of micromechatronics in surgery.

Key words: endoscopy; mechatronics; robotics; surgery.

1. Introduction

The word 'surgery' traditionally means making an incision large enough for the surgeon to see and feel the organs with his/her own eyes and fingers. Very often, the damage done to skin, muscle, connective tissue and bone, to reach the region of interest, causes much greater injury than the curative procedure itself (Tendick *et al.*, 1998). This normally results in more pain and trauma to the patient, longer recovery times and ultimately, higher costs. The trend is now moving towards minimally invasive therapy (MIT). The term MIT refers to all of the diagnostics and surgical procedures that employ instruments inserted into the body through natural orifices or small artificial punctures. The term minimally invasive surgery (MIS) is normally used to indicate the application of MIT in surgery (Dario *et al.*, 1996a, b). The main objective of MIS is to operate only on pathological organs

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and to preserve, as much as possible, all surrounding healthy organs and tissues. As such, recovery time, postoperative pain, infection risks and costs are reduced dramatically. Presently, MIT has already been introduced into medical fields like urology, gynaecology, abdominal surgery and orthopaedics. MIS has been implemented in laparoscopic, thorascopic, endoluminal and arthroscopic interventions (Taylor *et al*., 1996). With its fast growing acceptance, MIS could change the manner in which many other types of surgery are traditionally performed.

Mechatronics, the merger of mechanical and electronics engineering, first evolved in bigger machines like automobiles. Since then, mechatronic devices have been dramatically scaled down to cater to new and exciting needs. The size of miniature mechatronic devices, like portable video cameras and compact disc players, usually lies in the range of a few centimeters to about 1 m. Micromechatronic devices would lie in the range of a few microns to 1 cm, which is our area of interest in this review. Nanomechatronic technologies have also started to investigate technologies for fabricating devices less than 1 μm. Micromechatronics have played an important role in the evolution of MIS; its impact in the field of medicine had been envisaged by the micromechatronics research community (Knieling, 1991; Fujimasa, 1992). The concepts and technologies of micromechatronics are derived from those of mechatronics through the miniaturization of precision mechanisms, sensors, actuators and embedded electronics, and their 'harmonious' integration into smaller systems. In fact, it is this reduction of size of useful mechatronic devices which makes micromechatronics so attractive to MIS. They have great potential in allowing access to body cavities currently inaccessible. They also allow the possibilities of enhancing the surgeon's abilities where current MIS techniques do not permit the full range of human dexterity and perception. However, it is important to note that problems do arise from introducing micromechatronic devices into the human body. These include material compatibility, electrical hazard, energy supply and heat dissipation, to mention just a few. These have long been addressed by the medical and biomedical engineering communities, but at this present time, not all have been solved satisfactorily.

This review begins by defining the objectives and roles of micromechatronics in surgery. Thereafter, examples on its applications will be shown with reference to ongoing research in the authors' laboratories and other research centres.

2. Objectives and roles

In most cases of MIS, the surgeon normally does not come in direct contact with the tissue of interest. The sense of touch is impaired and the dexterity of surgical tools is limited to only a few degrees of freedom. Even the surgeon's depth perception is eliminated since he/she can only rely on images from a single camera. However, the high standards and safety of the surgical interventions cannot be compromised and this is where micromechatronic technologies become useful. Like medical robotics (Preising *et al*., 1991), micromechatronic devices have advantages over human surgeons. These include geometrical accuracy, constant and untiring performance, tremor-free movements, to name just a few. However, they lack the adaptability, experience and responsibility of the human surgeon. As such, a synergy between man and machine would bring together the advantages of both parties, whereby certain skilled tasks could be performed better than either one can do alone. Figure 1 shows the general layout of a micromechatronic surgical system. There are many areas in surgery where micromechatronics can make a difference for the better. In most cases, both the surgeon and patient benefit from it. The patient can expect less pain and trauma, shorter recovery time and lower costs. The surgeon, on the other hand, will be able to perform more efficiently, more accurately and with less fatigue.

2.1 Improved accessibility

Accessibility remains one of the most challenging problems faced in MIS. In line with the objectives of MIS, remote human body cavities have to be reached with little or no damage to healthy living tissue. Presently, surgeons use flexible endoscopes for inspection and intervention of the gastrointestinal tract, ear, nose and other natural orifices present in the human body. These endoscopes are good examples of micromechatronic devices. They have onboard ultra-compact CCD cameras, optical fibres and miniature cable actuators to bend its distal tip actively. Cleverly designed cable-actuated surgical tools can also be introduced via a tool channel which runs through the length of the endoscope. In the future, endoscopes could even be replaced by microrobots that can propel themselves autonomously in a tubular organ like the colon. The authors' MUSYC system (Carrozza *et al.*, 1996; Dario *et al.*, 1999), which will be discussed later, is an example of such a microrobot.

Researchers are also looking into ways to make catheters more 'intelligent', while retaining their miniscule sizes. The use of shape memory alloy (SMA) microactuators enables active bending of the catheter's distal tip. Furthermore, the integration of an array of microtactile sensors permits the catheter to be threaded along a path of least resistance, thus avoiding possible damage to the

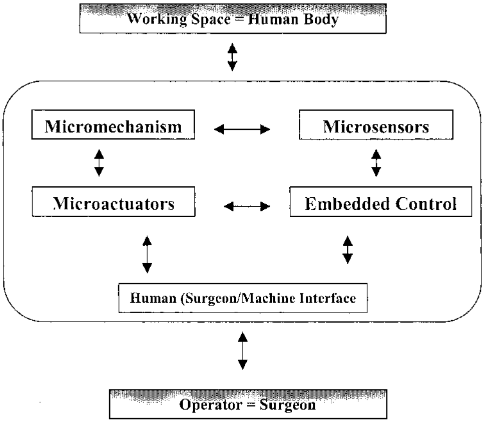

Figure 1 Layout of a micromechatronic surgical system

vessel walls (Negoro *et al.*, 1994). In the area of keyhole surgery, surgical tools are introduced into incisions of less than 1 cm. Similarly, by integrating such SMA actuators, as well as other types of microactuators and micromanipulators, the degrees of freedom (DOFs) of the tool can be increased, enabling the surgeon better to reach the organ of interest without unnecessary contact with surrounding healthy organs.

2.2 Enhanced dexterity and accuracy

It is amazing how our hands can adapt to perform an infinite number of different tasks. They are often used as a yardstick when we compare the dexterity of man-made manipulators. The success of traditional 'opensky' surgery is almost solely dependent on the performance of the surgeon's hands. Being in direct contact with the organ of interest, an experienced surgeon with steady hands would generally take less time to perform an operation and inflict less damage on healthy tissue as compared with an inexperienced surgeon. In MIS, however, the privilege of space is often absent. For example, in laparoscopic surgery, long and rigid instruments are inserted through cannulas to reach the organ of interest. In this scenario, the surgeon's dexterity is drastically reduced due to mechanical constraints which limit the number of DOF of the tool. The difficulty of performing delicate surgical manoeuvres like suturing and knot tying (Tendick *et al.*, 1993) is increased. Accuracy is another major concern in MIS. Tremor, which is undesirable in surgery, can result from the strain and fatigue derived from working long hours under these mechanical constraints. There are also procedures in microsurgery whereby the position resolution of the human hand is insufficient. To solve these problems, rigid and flexible endoscopes with steerable distal ends with at least one DOF are presently in use. They are controlled externally by manually turning 'angulation' knobs. To further enhance dexterity, microarms and micromanipulators with high DOFs will soon be available thanks to micromechatronic technologies. The movements of these devices would be teleoperated by the surgeon in a typical 'master-slave' configuration as depicted in Figure 2. The surgeon's motions are scaled down such that a large translation made by the master controller would cause the slave micromanipulator to be moved only a fraction of the distance. Such a system would improve dexterity and accuracy as it relieves most of the surgeon's technical difficulties.

2.3 Enhanced perception

In conventional open surgery, the surgeon relies on his/her sense of touch and sight to obtain information about tissue and organ consistency, homogeneity and pulsation. These are fundamental for intraoperative diagnostic differentiation and for planning suitable therapy. These senses, especially the sense of touch, are heavily impaired in most cases of MIS. To compensate for the loss of human touch, future MIS instrumentation will incorporate microsensors at the distal tip which are able to measure physical parameters of the tissue of interest and provide tactile

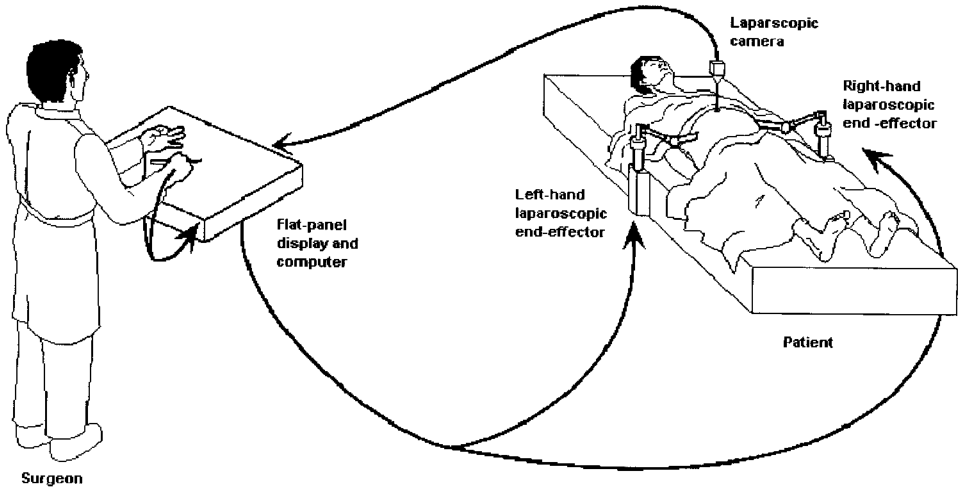

Figure 2 'Master–slave' configuration of a teleoperated surgical system

feedback to the surgeon. Force feedback is another area of consideration when designing surgical tools for MIS. For example, to avoid excessive bone and tissue trauma during orthopaedic drilling procedures, torque and normal force sensors could be incorporated into the drilling tool. In the area of vision, a camera is normally inserted into the body to obtain visual feedback for the surgeon. What is seen is a two-dimensional (2D) image on a TV monitor. Depth perception in a 3D working field is lost and a frequent consequence is the difficulty for the surgeon to identify accurately the relative position of the instruments being manipulated with respect to the organ of interest. This severely affects hand–eye co-ordination and spatial perception capabilities. Other main limitations of current vision systems are their poor colour reproduction and illumination. To overcome these problems, a number of devices have been proposed. These include compensating lenses for reducing image distortion and liquid crystal display (LCD) glasses for stereoscopic images. However, there is yet to be a system capable of providing high-resolution 3D vision to the surgeon. A possible solution of the lack of reference for the surgeon during MIS is augmented reality (Tang and Ng, 1998) whereby appropriate techniques are used to 'match' preoperative and intraoperative images.

2.4 Improved diagnosis procedures

Another possible use of micromechatronics in surgery is in the area of diagnosis. Noninvasive real-time diagnosis of the tissue of interest can be obtained by incorporating temperature, biochemical and micro-optical sensors into surgical tools. The real-time diagnosis of the tissue's pathology would allow the surgeon to decide, on the spot, a suitable therapy, reducing the need for follow-up surgeries.

3. Applications

3.1 Endoscopic surgery

The main objective of endoscopic surgery is to perform inspection and surgical procedures by inserting long instruments, called endoscopes, into natural orifices or small incisions. Endoscopes, either rigid or flexible, would normally have onboard an ultra-compact CCD camera, optical fibres, air/water channels and a surgical tool channel. In some models, actuating cables are used actively to bend the distal tip to 'look around' the body cavity and also to position a surgical tool for interventive purposes. The drawbacks of the present endoscope are its lack of dexterity and the technical difficulties involved in introducing the scope efficiently into the human body without traumatizing the patient. Colonoscopy is one of the most technically demanding endoscopic examinations. It is an art to coax an almost 2-m long flexible endoscope, called a colonoscope, around a tortuous colon whilst causing minimal discomfort and yet performing a thorough examination. An inexperienced surgeon may take a longer time to perform the procedure, cause more pain and trauma and could even perforate the colonic walls (Phee *et al.*, 1997). Researchers have started to look into the possibilities of improving the conventional colonoscope. Ikuta *et al.* (1988) used SMAs to develop an automated endoscope. They made use of the resistance of the SMA actuators in their feedback control scheme to guide their snake-like robot (Figure 3) around obstacles. The SMA springs are connected mechanically in parallel, but electrically in series. This arrangement increases the absolute value of electric resistance of the SMA without any reduction of its other performance. This also eliminates the need for sensors such as potentiometers and encoders. The driving mechanism of each segment consists of a stainless steel coil spring which acts as the main skeleton at the centre of a joint, and a series of SMA coil springs arranged around it. In this model, one segment has one DOF, so that a pair of SMA actuators capable of antagonistic motion are arranged in symmetry with respect to the axis. It is this antagonistic activation of the SMA springs that brings about the required bending motion. The basic design of the active endoscope model was conceived by considering its application to a fibresigmoidscope. For this purpose, it has enough mechanical compliance to pass the sigmoid colon, which has the smallest radius of curvature, smoothly. Fukuda *et al.* (1989), developed an in-pipe inspection robot capable of

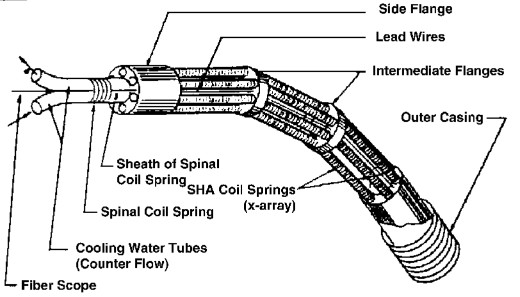

Figure 3 Inner structure of Ikuta *et al.*'s active endoscope

moving inside pipelines of nuclear power stations and chemical plants. It uses rubber gas actuators, which are lightweight and flexible enough to make very acute turns. Although this robot was designed for industrial applications, it could be modified for use as a colonoscope. Sturges *et al.* (1991), designed a flexible, tendon-controlled bead-chain device for endoscopy. This design employs what Sturges *et al.* call a 'slide motion scheme' to traverse the device into the colon. Burdick *et al.* (Grundfest *et al.*, 1995) invented a robotic endoscope, which uses inflatable balloons and rubber bellows as actuators, and comprises a plurality of segments attached to each other through an articulated joint. The inchworm mode of locomotion is employed in this design.

At the authors' laboratory, a team is currently developing an endoscopic micromechatronic system in the Multifunctional Minirobot System for Endoscopy (MUSYC) project which is funded by the European Union (Carrozza *et al.*, 1996; Dario *et al.*, 1999). The main objective of the robotic system is to maintain the multifunctionality of the conventional colonoscope, while eliminating the rigidness of the insertion tube that causes pain and discomfort for the patient. The system consists of a microrobot able to propel itself autonomously along the colon using the inchworm mode of locomotion. Presently, the project focuses mainly on the optimization of the locomotion principle of the microrobot. Fabrication of the microrobot requires extensive use of micromechatronic technologies like silicon micromachining and microelectrodischarge machining (μEDM). It can be divided into three actuating segments. The proximal and distal clamping actuators have the primary role of providing traction for the microrobot on the colonic walls, while the central bellow actuator extends or retracts the microrobot. These segments are pneumatically actuated. Either positive or negative air pressures are applied depending on the motion sequence, as illustrated in Figure 4. The microrobot has a flexible 'tail' which houses the electrical wires for sensing, actuating and control, and flexible tubes for channelling vacuum and pressurized air to the

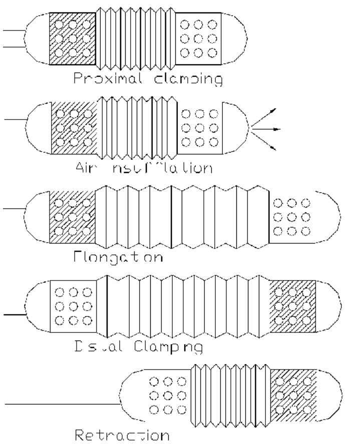

Figure 4 Locomotion sequence of the MUSYC microrobot. The shaded area on the distal and proximal clamping acutators indicate the active clamping states

mothership. The latest prototype (Figure 5) incorporates an ultra-compact CCD camera, optical fibre bundles, air/water channel and a surgical tool channel onboard the microrobot. Initial *in vitro* and *in vivo* experiments have yielded encouraging results. In the near future, this micromechatronic system will incorporate sensorized microtools teleoperated by the surgeon, so as to allow him/her to perform diagnostic interventions and dexterous surgical operations inside the large intestine. The team's future work also includes developing a SMA actuated steerable distal head for the microrobot. Using an array of microtactile sensors situated at its distal tip, it would be able to sense oncoming 3D bends in the colon and automatically bend its tip towards the path of least resistance.

Other researchers like Suzumori *et al*. (1991) have developed micromechatronic devices which can be used actively to bend the distal tip of an endoscope. This device consists of a flexible microactuator (FMA) which is driven by electropneumatics or electrohydraulics. The FMA has three DOFs – pitch, yaw and stretch – and is made in the likeness of the human finger, both in appearance and movement. Grundfest *et al*. (1994), proposed, in their patent, an embodiment of four distinct pressure inflatable microsacs arranged circumferentially around a central core. Co-ordinated inflation and deflation of the sacs would bring about active bending of the device.

3.2 Intravascular surgery

Catheters are long and slender surgical instruments used to treat vascular abnormalities. For example, to treat an aneurysm in cerebral vascular surgery (Negoro *et al*., 1994) a microcatheter is inserted into the thigh and threaded to the carotid artery in the brain. When the tip of the microcatheter reaches the site of the clot, a microcoil is delivered to occlude the aneurysm sac. The surgeon uses video X-ray images to view and guide the advancement of the microcatheter. Due to the lack of dexterity of present catheters, the threading of the microcatheter through complex vessels and branches is a tedious and difficult task for the surgeon.

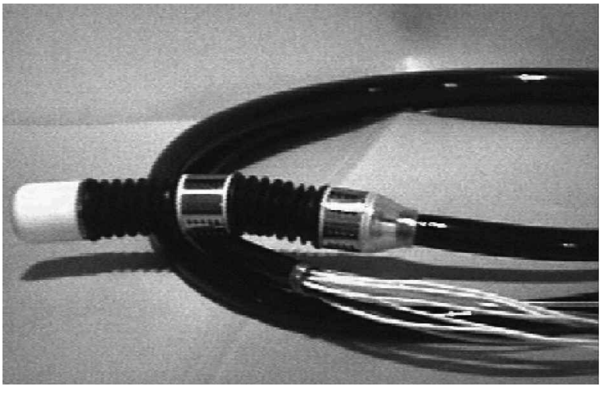

Figure 5 Latest prototype of the MUSYC microrobot

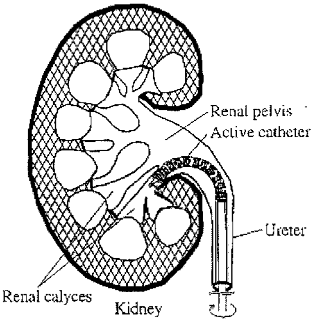

Figure 6 SMA acuated microcatheter actively bending in a kidney

Micromechatronic technologies could be used to develop highly dexterous microcatheters with diameters of less than 2 mm. Although SMA seems to be the favourite actuator used by researchers, electrostrictive polymer actuators (Ivanescu and Stoian, 1995; Della Santa *et al.*, 1996; Kornbluh *et al.*, 1998) are proving to be another possible alternative. Fukuda *et al.* (1994), in their bid to improve the conventional wire-guided medical catheter, have developed a microactive catheter (MAC) with two DOFs. The MAC is basically made up of three strips of SMA wires embedded at 120° intervals in a cylindrical housing made of elastic material. Haga *et al.* (1998) designed an active microcatheter actuated by distributed SMA coils. They also proposed mounting a miniature ultrasonic transducer onto their microcatheter to perform intraureteral ultrasonography of the kidney. Figure 6 shows the microcatheter actively bending towards the renal calyces, a part of the kidney presently unreachable by conventional catheters.

Narumiya (1993) have gone one step further by proposing the integrating of microtactile, pressure, flow rate sensors at the tip of a microcatheter, along with micronozzles and micropumps for local injection of drugs and solutions for dissolving thrombus. Tanimoto *et al.* (1998) incorporated a microforce sensor at the distal tip of their 1.6-mm-thick microcatheter. With their device, they aim to measure the contact forces between the catheter's distal tip and the walls of blood vessels, thus helping the surgeon to find the path of least resistance during the progression of the microcatheter. At Olympus Optical Co., Ltd, a highly dexterous 1.5-mm-thick microcatheter has been built by Takizawa *et al.* (1999). Figure 7(a)

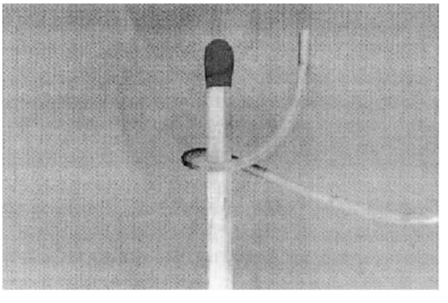

Figure 7 (a) The Olympus highly dexterous microcatheter. (b) MIF microtactile sensors mounted at the tip

shows the microcatheter bending around a match stick. It is actuated by SMA wires of diameter 0.075 mm. The team is also developing microtactile sensors using Multifunction Integrated Film (MIF) technology (Kaneko *et al.*, 1997). These are mounted at the distal tip of the microcatheter (Figure 7b) and are used to detect the vessel walls for navigation purposes.

3.3 Laparoscopic and arthroscopic surgery

First performed using simple instruments by a Swedish physician in 1910 (Sonderstrom, 1998), laparoscopic surgery has since developed into a technologically advanced surgical procedure. Present slender and rigid laparoscopic tools enter the abdomen through small incisions. Passive mechanics is used to actuate needle holders, graspers and other end effectors at the distal tip of the tool. Due to the lack of DOFs of these tools, surgeons can reach points within a 3D volume but cannot fully control orientation. Complex surgical procedures like suturing and knot tying are performed with great difficulty. Furthermore, with only a 2D image to rely on, the surgeon would normally have poor perception in identifying accurately the relative position of the instruments being manipulated with respect to the organ of interest. Furthermore, the surgeon's sense of touch is completely lost. Not being able to feel the tissue of interest could mean the loss of valuable information like tissue homogeneity and pulsation.

The recent introduction of the commercially available ZEUS robot surgical system is a major improvement in the field of MIS (Figure 8). With this advanced operating system, human and machine perform side by side. The surgeon teleoperates behind a 'master' console actuating 'slave' manipulators at the operating site. Its manufacturers claim that this system eliminates human hand tremor and allows the surgeon to scale down his/her hand movements to micromovements inside the body. According to some surgeons who have used the system, difficult procedures like suturing and knot tying are performed with greater ease. Other advantages include improved precision and dexterity, more realistic visualization and a more ergonomical working environment for the surgeon. This commercial system could be further improved with micromechatronic technologies.

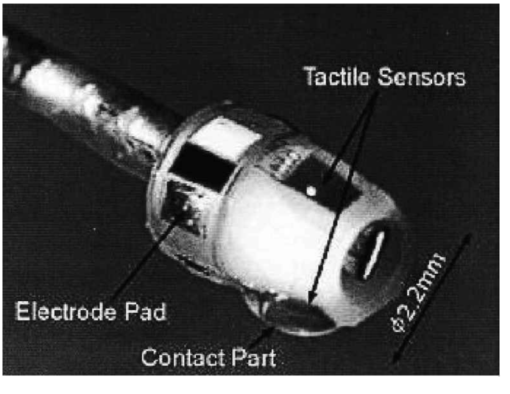

Figure 8 The ZEUS robotic surgical system

Microforce and tactile sensors could be attached to the 'slave' manipulators to sense the contact forces between the tissue of interest and the tool. This information can then be used to create artificial force and tactile feedback devices for the surgeon. For example when the tool comes in contact with the tissue, a mechanical resistance on the tool movement could be felt by the surgeon. This resistance would increase proportionally with the increase in contact forces between the tool and the tissue. A system like this would compensate, to a certain extent, for the surgeon's lost sense of touch.

In the research scene, the medical robotics group at University of California at Berkeley (Sastry *et al.*, 1997; Cavusoglu *et al.*, 1998) is developing multi-DOF end effectors with appropriate surgeon–machine interfaces to build laparoscopic manipulators that are more versatile and dexterous. When completed, this teleoperated workstation will incorporate two robotic 'slave' manipulators with dextrous manipulation and tactile sensing capabilities. The 'master' devices would be capable of force and tactile feedback including improved imaging and 3D display systems. The team's goal is to design a system which is both highly dextrous and intuitive to use, allowing complex surgical operations to be performed with minimally invasive techniques. Figure 9 shows the current design of the 'slave' manipulator. Its first stage consists of a Stewart platform-like parallel manipulator driven by electric motors giving four DOFs. The second stage is a three-DOF millirobot with a two-DOF wrist and a gripper, driven by hydraulic actuators.

The same group has also designed a miniature tactile sensor array (Gray and Fearing, 1996) to be mounted at the tip of their laparoscopic tool (Figure 10). This 1×1 mm sensor consists of an eight-by-eight array of capacitive sensor cells covered by a rubber layer that serves as a low-pass spatial filter. When pressure is applied to the array, the resulting deformation causes changes in capacitance of the affected cells. In this manner, not only can contact be detected, it can also be localized and a profile of contact forces surmized. A team from Harvard University is developing a palpation system (Howe *et al.*, 1994; Peine *et al.*, 1994) to convey information from inside a patient's body to the surgeon's fingertips during MIS procedures. Tactile array sensors are incorporated onto the end effectors of their surgical tools as shown in Figure 11. These are used to measure pressure distribution on the instruments as tissue is manipulated. The signals from

Figure 9 The Berkeley millirobotic manipulator

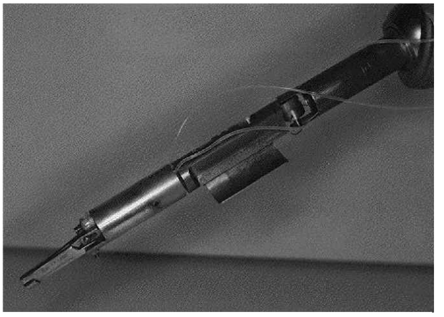

Figure 10 The Berkeley 1 × 1 mm tactile sensor array

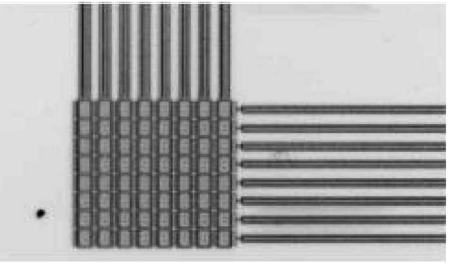

Figure 11 The Harvard remote palpation system

these sensors will be sampled by a dedicated computer system which will apply appropriate signal processing algorithms. Finally, the tactile information will be conveyed to the surgeon through tactile 'display' devices that recreate the remote pressure distribution on the surgeon's fingertips. The team hopes that this creation of remote palpation technology will increase safety and reliability in present MIS procedures.

Positioning error is inherent in normal human hand motion. This includes components such as physiological tremor, jerk and low-frequency wander. For a surgeon performing surgery, involuntary hand motion limits the accuracy with which he/she operates. This problem is especially significant in the fields of ophthalmological and neurological surgery. In complex laparoscopic procedures, inevitable tremors of the surgeon's hand is an undesirable occurrence, which becomes even more prominent when fatigue sets in. To address this problem, an intelligent active hand-held device capable of suppressing hand tremor is being developed at Carnegie Mellon University (Riviere and Khosla, 1997; Riviere *et al.*, 1998). This instrument senses its own motion, distinguishes between desired and undesired motion using advanced filtering techniques, and actively compensates for undesired motion by an equal but opposite deflection of its own tip. A full prototype with six sensors and three actuators is shown in Figure 12(a), while Figure 12(b) shows some promising experimental results of its error compensation capabilities. Other research groups (Faraz *et al.*, 1995; Nakamura *et al.*, 1995; Bicchi *et al.*, 1996; Lazeroms *et al.*, 1996; Schurr *et al.*, 1996) have also proposed and built innovative micromechatronic devices for access and manipulation in laparoscopy.

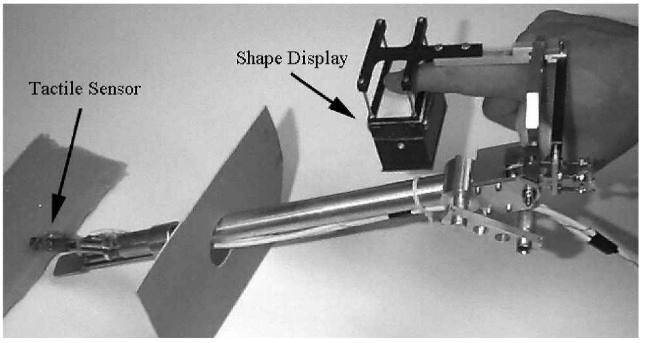

Figure 12 (a) Prototype of hand tremor suppressing device. (b) Experimental results of the prototype's error compensation capabilities

In the field of arthroscopic surgery, the authors' laboratory is involved in the Minimally Invasive Articular Surgery (MIAS) project which is funded by the European Union. The aim is to develop an enhanced reality system to help surgeons to use multimodal data (images, forces, planned procedures) in a fully integrated and effective manner (Dario *et al.*, 2000). Another objective of the project is to use micromechatronic technologies to develop a novel tool for computer-assisted arthroscopy. The new mechatronic arthroscope has a cable-actuated, servomotor driven, multijoint mechanical structure. It is equipped with miniature Hall effect sensors, which measure the orientation of the distal tip, and a microforce sensor to detect possible contact with delicate tissues. It also incorporates an embedded microcontroller for sensor signal processing, motor driving and interfacing with the surgeon and/or the system control unit. When used manually, the mechatronic arthroscope enhances the surgeon's capabilities by enabling him/her to control the tip motion easily and to prevent undesired contacts with tissues. When the tool is integrated in a complete system for computer-assisted arthroscopy, the trajectory of the arthroscope is reconstructed in real time by an optical tracking system using infra-red emitters located in the handle which provides advantages in terms of improved intervention accuracy. Figure 13 shows the mechatronic

Figure 13 The mechatronic arthroscope in an experimental set-up of knee arthroscopy

arthroscope in an experimental set-up of knee arthroscopy. The computer-assisted arthroscopy system comprises an image processing module for segmentation and 3D reconstruction of preoperative CT or MR images; a registration module for measuring the position of the knee joint, tracking the trajectory of the operating tools, and matching preoperative and intraoperative images; and a human–machine interface that displays the enhanced reality scenario and data from the mechatronic arthroscope in a friendly and intuitive manner. By integrating preoperative and intraoperative images, and information provided by the mechatronic arthroscope, the system allows virtual navigation in the knee joint during the planning phase, and computer guidance by augmented reality (Tang *et al.*, 1998) during the intervention.

3.4 Microsurgery

There is an increasing need to grasp and manipulate small or microobjects in the fields of medicine and biology (Hunter *et al.*, 1989; Dario and Carrozza, 1997; Mitsuishi *et al.*, 1997). This is especially true in microsurgery: a sophisticated surgical technique which involves the use of fine instruments and visual magnification to allow the surgeon to carefully manipulate very small structures. Replantation surgery, the reattachments of severed limbs, is the most famous example of microsurgery. In this operation, severed vessels and nerves of diameters less than 1 mm are tediously reconnected. Microsurgery has since been introduced in neurosurgery, gynaecology and urology.

It is apparent that conventional surgical instruments are too bulky to be used in microsurgery, where the position resolution of the human hand is pushed to or beyond its limit. What are required to improve the present situation are accurate and dexterous micromechatronic tools with high position resolutions. Since 1994, a group from National Aeronautics and Space Administration (NASA) has been developing a new robotic microdexterity platform called Robot Assisted MicroSurgery (RAMS) (Schenker *et al.*, 1995; Das *et al.*, 1996), which will enable new microsurgical procedures of the brain, eye, ear, nose, throat, face and hand. The RAMS workstation consists of a six-DOF master–slave telemanipulator with programmable controls. The primary RAMS control mode is telemanipulation, which includes task-frame referenced manual force feedback and textural feedback. The operator will also be able interactively to designate or ‘share’ automated control of robot trajectories. NASA claims that this system not only refines the physical scale of state-of-art microsurgical procedures, but also enables more positive outcomes for average surgeons during typical procedures.

Researchers are also developing microtools for better manipulation of tissues in microsurgery. At the authors’ laboratory, several microgripper prototypes (Carrozza *et al.*, 1998) actuated by piezoelectrics, have been designed and fabricated. Traditional precision machining and laser cutting technologies were used to fabricate the earlier prototypes. However, LIGA (in German: Lithographie, Galvanoformung, Abformung) was employed for the latest prototype due to the unique advantages it can offer in the fabrication of structures with high aspect ratios (Ehrhard and Munchneyer, 1991). The ‘finger’ of this 200-μm-thick

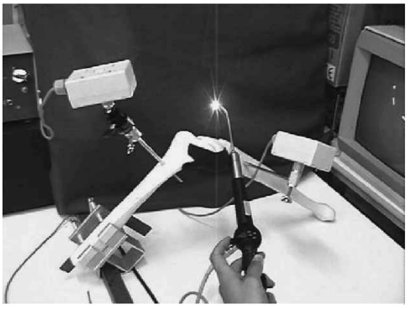

Figure 14 Manipulation of an insect's ovarian follicle by the LIGA-fabricated microgripper

microgripper was designed to have a displacement of between 100 to 200 μm each. Figure 14 shows an insect's ovarian follicle being manipulated by the LIGA-fabricated microgripper. The group's future work includes the development of new, gold-coated microgrippers, sensorization of the microgrippers using displacement and force sensors, and the development of a new controller and suitable interface for improved 3D teleoperation. In addition to the development of a variety of microgrippers by other researchers, innovative micromechatronic surgical tools like microforceps (Nakamura *et al*., 1995), microtweezers (MEMS Precision Instruments), and microscissors are also slowly evolving. These 'smart' instruments are highly dexterous and could be teleoperated by the surgeon. Figure 15

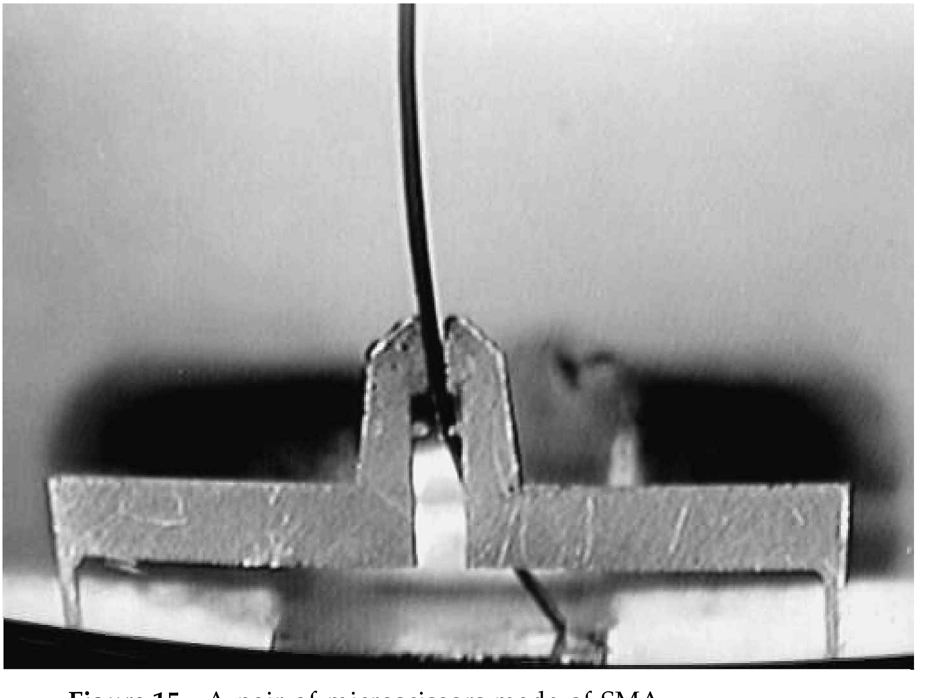

Figure 15 A pair of microscissors made of SMA

shows a pair of microscissors fabricated from a 0.63-mm-thick SMA wire using μEDM.

4. Conclusion

The objectives and roles of micromechatronics in surgery have been discussed in this paper. An extensive review of the state of the art has also been illustrated with many examples of practical applications from both the research and industry sectors. It can be envisioned that in the near future, micromechatronic technologies will have an even greater impact in the field of surgery. Surgeons can be more relieved from technical difficulties while patients can suffer less pain and discomfort. Although there are many advantages in introducing micromechatronic devices into the operating theatre, safety (Davies *et al*., 1996) and biocompatibility are some critical issues that cannot be compromised on. It is also important to note that surgical solutions are not just about developing devices. Rather, a 'system approach' should be adopted to realize whole systems that exploit both human and machine capabilities. There is also the 'human factor' to be considered when introducing a new technology like micromechatronics into a people-oriented profession like surgery. Time is required for both surgeons and patients alike to become accustomed to new surgical practices where machines contribute more to the success of the operations.

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